Water vapor and the transition to strong convection

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• Issues with precip. simulation, esp. at regional scales, tropics: global warming, El Niño..., Sensitivity to convective schemes
e.g., IPCC 2001, 2007; Trenberth et al 2003; Maloney and Hartmann 2001; Joseph and Nigam 2006; Biasutti et al. 2006; Dai 2006; Tost et al. 2006; Neelin et al 2007; Bretherton 2007...

1. Sensitivity of convective margin zones

2. Characterizing transition to deep convection
   - dependence on temperature and water vapor
   - remote sensing statistics and buoyancy calculations from vertical structure

3. Long tails in distributions of column tracers
Issues with precipitation simulation, especially at regional scales, tropics: global warming, El Niño…

- Sensitivity to convective schemes, interaction with large-scale
- [although some agreement on large-scale or amplitude]


4 mm/day model climatology black contour for reference

e.g., IPCC 2001, 2007; Trenberth et al 2003; Maloney and Hartmann 2001; Joseph and Nigam 2006; Biasutti et al. 2006; Dai 2006; Tost et al. 2006; Neelin et al 2006; Bretherton 2007...
1. Sensitivity at convective margin
Prototype model*: dry advection into a precipitating region

Precipitation (green) and moisture (contours) would be constant except for trade wind inflow

- Temp. & moisture equations, specified wind + Gaussian variations;
- Analytic solutions for interplay with local thermodynamics and convective threshold

Lintner & Neelin 2008, GRL
Prototype model: change in threshold for convection

Precipitation (green) and moisture (contours)

Substantial impact of a poorly constrained aspect of convective schemes

Lintner & Neelin 2008, GRL
South Pacific Convergence Zone (SPCZ) composites: SSMI precip, column water vapor on wind variations

Daily SSMI

Composites on u925 mb avgd 140°W-120°W, 20°S-10°S.

4 mm day$^{-1}$ (weaker trades/less low-level dry air inflow)

4 mm day$^{-1}$ (stronger trades/more low-level dry air inflow)

Lintner & Neelin (2008)
Precip. composite on local inflow wind anomaly

Inflow wind $v_{\nabla P}$ across gradient of mean precipitation

Atmospheric boundary layer (ABL) wind

Large sensitivity at margin

Ratio to composite on precipitation

Locally, monthly composite precipitation differences associated with inflow represent 80-90% of total composite-differenced precipitation

Lintner & Neelin (2009, subm)
2. Transition to strong convection

- **Convective quasi-equilibrium assumptions**: Above onset threshold, convection/precip. increase keeps system close to onset. Arakawa & Schubert 1974; Betts & Miller 1986; Moorthi & Suarez 1992; Randall & Pan 1993; Zhang & McFarlane 1995; Emanuel 1993; Emanuel et al 1994; Bretherton et al. 2004; …

- **Pick up a function of buoyancy-related fields** – temperature $T$ & moisture (here column integrated moisture $w$)

- **Elsewhere**: Onset of strong convection conforms to list of properties for continuous phase transition with critical phenomena (Peters & Neelin 2006, Nature Physics); mesoscale implications (Peters, Neelin & Nesbitt 2009, JAS)

- **Stochastic convective schemes** (and old-fashioned schemes too) need to better characterize the transition to deep convection
Precip. dependence on tropospheric temperature & column water vapor from TMI*

• Averages conditioned on vert. avg. temp. $\hat{T}$, as well as $w$ ($T$ 200-1000mb from ERA40 reanalysis)

• Power law fits above critical:

  $P(w) = a(w-w_c)^\beta$

  $w_c$ changes, same $\beta$

• [note more data points at 270, 271]

* TMI: Tropical Rainfall Measuring Mission Microwave Imager (Hilburn and Wentz 2008), 20N-20S

Neelin, Peters & Hales, 2009, JAS
Collapsed statistics for observed precipitation

- Precip. mean & variance dependence on $w$ normalized by critical value $w_c$; occurrence probability for precipitating points (for 4 $T$ values); Event size distribution at Nauru
Example from Manna (1991) lattice model
(hopping particles—not a model of convection! 20x20 grid shown)

• Activity (order parameter) & variance dependence on particle density (tuning parameter) [conserving case]
• Occurrence probability (log scale; very Gaussian) & event size distribution [self organizing case]
**Critical point dependence on temperature**

- Find critical water vapor $w_c$ for each vert. avg. temp. $\hat{T}$
- Compare to vert. int. saturation vapor value binned by same $\hat{T}$
- *Not* e.g., a constant fraction of column saturation
- Lower tropospheric saturation $q_{\text{sat}}(T)$ binning gives same results

Neelin, Peters & Hales, 2009, JAS
Saturation value $q_{\text{sat}}(T)$ by level

- Saturation mixing ratio by level binned by vert. avg. temp. $\hat{T}$
- Compare to critical value & vert. int. saturation value vs. $\hat{T}$
- Appears consistent with substantial control by lower free troposphere proximity to saturation
Check pick-up with radar precip data

- TRMM radar data for precipitation
- 4 Regions collapse again with $w_c$ scaling
- Power law fit above critical even has roughly same exponent as from TMI microwave rain estimate
  - (2A25 product, averaged to the TMI water vapor grid)

Peters, Neelin & Nesbitt, JAS, 2009
Entraining convective available potential energy and precipitation binned by column water vapor, $w$

- buoyancy & precip. pickup at high $w$
- boundary layer and lower free tropospheric moisture contribute comparably*
- consistent with importance of lower free tropospheric moisture (Austin 1948; Yoneyama and Fujitani 1995; Wei et al. 1998; Raymond et al. 1998; Sherwood 1999; Parsons et al. 2000; Raymond 2000; Tompkins 2001; Redelsperger et al. 2002; Derbyshire et al. 2004; Sobel et al. 2004; Tian et al. 2006)

*Brown & Zhang 1997 entrainment; scheme and microphysics affect onset value, though not ordering.  
Holloway & Neelin, *JAS*, 2009  
Binning \( q \), precip. on vert. int. water vapor

Spec. humidity, \( q \)  
Precip.

Binned by: Column water vapor

850-200 mb

Surface-950mb

[Note fewer soundings in high bins]

Nauru ARM site observations

Holloway & Neelin, JAS, 2009
Lifted parcel buoyancy by column water vapor bins

No mixing

Const. mixing (Brown & Zhang 1997)

Const. mixing, with \( q \) in free troposphere constant

Const. mixing, only \( q \) in free troposphere changes

- Highest column water vapor bins most buoyant
- Both boundary layer and lower free troposphere contribute
Lifted parcel buoyancy by column water vapor bins

- Deep inflow mixing A
- Deep inflow mixing B
- Deep inflow mixing A with instant freezing (reversible)
- Deep inflow mixing B with instant freezing (reversible)

- Highest few column water vapor bins deep convective microphysics between these cases; large potential impact
Prec & column water vapor: autocorrelations in time

- Long autocorrelation times for vertically integrated moisture (once lofted, it floats around)
- Nauru ARM site upward looking radiometer + optical gauge

Precip conditioned on lag/lead column water vapor

- High water vapor several hours ahead still useful for pickup in precipitation
- Consistent with high water vapor $\Rightarrow$ favorable environment, but stochastic plume
- Nauru ARM site upward looking radiometer + optical gauge

Holloway & Neelin JAS subm.
How do models do? CAM3.5 (0.5 degree run) *
Precip. dependence on tropospheric temperature & column water vapor

• Averages conditioned on vert. avg. temp. $T$, as well as column water vapor $w$
• Linear fits above critical (motivated by parameterizn)
$P(w)=a(w-w_c)^\beta$
as obs. but $\beta=1$ : to estimate $w_c$

*Runs, data R. Neale, analysis K. Hales
Critical point dependence on temperature

CAM3.5 preliminary comparison

- Critical water vapor $w_c$ for each vert. avg. temp. $\hat{T}$
- Compare to vert. int. saturation vapor value binned by same $\hat{T}$
- Suggests suitable entraining plumes can capture $T$ dependence
Obs. Freq. of occurrence of $w/w_c$ (precipitating pts)

Eastern Pacific for various tropospheric temperatures

- Peak just below critical pt. $\Rightarrow$ self-organization toward $w_c$
- But exponential tail above critical pt. $\Rightarrow$ more large events

- with Gaussian core, akin to forced tracer advection-diffusion problems
  (e.g. Shraiman & Siggia 1994, Pierrehumbert 2000, Bourlioux & Majda 2002)
Precipitating freq. of occurrence vs. $w/w_c$
Eastern Pacific for various tropospheric temperatures
- CAM3.5 preliminary comparison
- Includes super-Gaussian ~exponential range above critical pt.
Summary

• These statistics for precipitation and buoyancy related variables at short time scales provide new ways to quantify the transition to tropical deep convection as needed for models

• Tracer distributions consistent with simple prototypes; core with stretched exponential tails ubiquitous

   Current retrievals are great but could sure use
• vertical dependence on temperature and water vapor in deep convective regions, land,…
• Coordinated observations of condensate loading, freezing
• huge number of observations allow statistics to the computed consistently through range with large events

• Multiple tracers promising